

DM2120.

Chairperson E. Lessard called the second meeting in 2005 of the Laboratory Environmental Safety and Health Committee (LESHC) to order on January 19, 2005 at 1:45 p.m.

1. **Superconducting Undulator (SCU) Magnet, Phase 1 Testing – Informational Meeting:** E. Lessard invited J. Skaritka of the National Synchrotron Light Source Department, to discuss the Superconducting Undulator Magnet Development Program with an emphasis on the planned Phase 1 testing¹.
 - 1.1. Mr. Skaritka and other attendees made the following points during the course of the presentation and in response to specific Committee questions:
 - 1.1.1. This is an information meeting to introduce the Committee to the Superconducting Undulator (SCU) Development Project. Formal presentations for each of the two testing phases will be made to the Committee prior to the start of cold testing.
 - 1.1.2. The proposed NSLS II will require Superconducting Undulator Magnets (SCUs) with shorter periods, higher fields and associated greater cryogenic heat loads.
 - 1.1.3. This project will develop and test NSLS II SCU prototypes. The testing will occur in the Vertical Test Facility (VTF), a BNL apparatus with magnetic and thermal measurement capability and the ability to simulate beam tube heat loads.
 - 1.1.4. Some of the SCU prototypes may be developed and fabricated at other National Laboratories for testing in the VTF, but the focus of this discussion is the Phase I testing of the VTF. The Phase I test will use an existing BNL SCU to test the VTF and the associated magnetic measurement devices. The testing will be first done warm and then cold, under liquid helium (LHe) pool boiling conditions. Phase I testing is scheduled for mid 2005.
 - 1.1.5. The Phase II testing is scheduled to take place in early 2006. The testing configuration will be a closed LHe system that is pressurized to approximately 30 psig to maintain subcooled conditions throughout the test apparatus. This phase will also include heat input to simulate expected NSLS II heat loads.
 - 1.2. In preparation for the formal presentation of the Phase I SCU testing to the LESHC, the Committee offers the following input:
 - 1.2.1. Develop a Memorandum of Understanding (MOU) between the NSLS and the Magnet Division to formalize the testing process and to communicate any assumptions (e.g., continuous ventilation) that are credited in the safety calculations. Provide a copy of the signed MOU to the LESHC Secretary for the Record.
 - 1.2.2. Submit the formal ODH calculation for the VTF testing location. The calculation should account for co-located cryogenic inventories and pre-existing controls.

¹ Mr. Skaritka's presentation and these Minutes are posted on the LESHC website: http://www.rhichome.bnl.gov/AGS/Accel/SND/laboratory_environment_safety_and_health_committee.htm.)

- 1.2.3. The VTF has components (e.g., the test can, ceramic isolator, bellows and Conflat flanges) that are not pressure rated. Please provide the Manufacturer's design pressure rating, or perform proof testing in accordance with ASME Boiler and Pressure Vessel Code requirements, or use pressure rated components. Kindly submit this information to the LESHC Secretary.
 - 1.2.4. Refer to the "Guidelines for Developing Procedures" in the SBMS Subject Area, "Internal Controlled Documents"
<https://sbms.bnl.gov/standard/06/0600t011.htm> (or the equivalent NSLS guidance) and rework the SCU testing procedure. Please include a P&ID (Piping and Instrumentation Diagram) and identify critical software controls in the procedure. Ensure the procedure and its attachments are in configuration control. Kindly submit a copy of the approved procedure to the LESHC Secretary.
 - 1.2.5. Please review the SBMS Subject Area, "Lifting Safety" and address all requirements. The Committee notes that the VTF may satisfy the criteria for a critical lift, and the tophat appears to be a "below the hook lifting device".
 - 1.2.6. Submit an approved Experimental Safety Review or a VTF Work plan for Committee review. In the longer term, write and submit a hazards analysis for the test facility. Consult the SBMS Subject Area, "Hazard Analysis" to determine the type of hazards analysis that is suitable for the VTF.
 - 1.2.7. The relief valve discharges must be directed away from personnel.
 - 1.2.8. All pressure gauges must be calibrated.
 - 1.2.9. Contact the Laboratory Electrical Safety Committee and arrange for an electrical inspection of the VTF.
 - 1.2.10. Ensure that all instrumentation is stamped by a Nationally Recognized Testing Laboratory
 - 1.2.11. Contact the LESHC Secretary to arrange for a walk through of the Phase I SCU Test Configuration prior to the formal Committee review.
2. The Meeting was adjourned at 3:20 p.m.

THE SUPERCONDUCTING UNDULATOR PROTOTYPE TEST FACILITY AT BROOKHAVEN NATIONAL LABORATORY

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Abstract

Users of Modern third generation Synchrotron Light Sources require ever brighter X-ray beams to perform their research. The beam brightness is controlled by accelerator capability and the parameters of the undulator magnets used in the insertion devices. Parameters such as very short magnetic period length (1-2 cm), small magnetic gap (0.5-1 cm), very high magnetic fields (1.5-2 tesla), and a wide tuning range of magnetic field strength (more than 4:1) are required to achieve this next level of machine brightness. This combination of requirements can only be met with superconducting magnet technology. However, third generation light sources generate substantial heat from image currents of the high-power electron beam, as well as from intense synchrotron radiation from upstream magnets may limit the performance of superconducting insertion devices.[1] To meet the challenges of SCU undulator design and testing, BNL has entered into a collaboration with three other US National Laboratories. The goal of this collaboration is to develop SCU technology that will successfully address the high heat load, the above desired parameters and SCU field correction.[2] BNL's contribution to the collaboration is for the NSLS to build a cryogenic test facility for comprehensive calorimetric as well as magnetic measurements of short SCU prototypes up to about 0.5m long. This SCU "vertical test facility" (VTF) is uniquely designed to test SCU models under realistic operating conditions with simulated beam heating loads up to 100 watts/m of length.

1. Introduction

Undulator magnets are used in high-energy electron accelerators, like synchrotrons or electron storage rings ("synchrotron light sources"), to generate extremely intense, nearly monochromatic x-ray beams, which are used in many fields of basic research, including material science, chemistry and, most recently, in the decoding and 3-dimensional imaging of complex biological molecules.

To date, most undulators have been assembled from permanent magnets; however, this technology is mature and near its theoretical limits. Modern "third generation" synchrotron light sources require undulators with a combination of very short magnetic period length (1-2 cm), small magnetic gap (0.5-1 cm), very high magnetic fields (1.5-2 tesla), and a wide tuning range of magnetic field strength (more than 4:1). This combination of requirements can only be met with superconducting (SC) magnet technology. In a superconducting undulator (SCU), coils or windings of superconducting wire, carrying currents in excess of 1,000 amperes per square millimeter (A/mm^2) of conductor cross-section, are wound around or between ferromagnetic poles. SCU's wound with the commonly available niobium-titanium (NbTi) superconductors have been demonstrated recently. However, the higher performance requirements described above call for even higher current densities, necessitating use of more exotic SC materials like Nb_3Sn , NbAl or NbTi with artificial pinning centers (APC-NbTi).

As in all superconducting magnets, the SC wire must be cooled to a temperature below its "critical temperature" (T_c), typically a few degrees Kelvin. Modern cryostat designs can limit heat transfer from the environment to the superconductor to the order of 1 watt at 4K, which can readily be removed by a cryocooler or by a liquid helium refrigerator. However, third generation light sources may generate substantial additional heat from image currents of the high-power electron beam, as well as from intense synchrotron radiation from upstream magnets, and other beam-related effects. This heat appears in the walls of the evacuated beam tube which is situated between the magnet arrays and provides a flight path for the electron beam through the undulator's magnetic field. (Note that a beam tube is generally required to isolate

the ultrahigh vacuum of the electron storage ring from the SC magnet coils which are typically insulated with organic materials and are not compatible with ultrahigh vacuum.) This heat must be removed, otherwise it may warm the SC wire above T_c , causing it to suddenly become normal conducting (“quench”) and resulting in collapse of the magnetic field at best, or, at worst, in catastrophic failure of the magnet. An efficient system of thermal management and cryogenic cooling is needed for superconducting undulators to be used in the newest and proposed synchrotron light sources.

To meet the challenges of SCU undulator design and testing, we are constructing at NSLS a cryogenic test facility for comprehensive calorimetric as well as magnetic measurements of short SCU prototypes up to about 0.4m long. This SCU “vertical test facility” (VTF) is uniquely designed to test SCU models under realistic operating conditions with simulated beam heating loads up to 100 watts/m of length.

2.0 SCU Magnet Development and the US Intra-laboratory Collaboration

BNL has proposed to build NSLS II, a ultra high brightness medium energy short pulse Synchrotron Radiation Facility. Various phenomenon have been identified that contribute to the cryogenic heat load deposited into the cold mass of the SCU. Cold mass heat loads as high as 5 watts per meter of SCU length have been estimated. The history of synchrotron radiation sources show that dramatic improvement in brightness often occurs over time. Using BNL’s NSLS as an example X-ray brightness has increased by a factor of more than a 1000 since operation began over twenty years ago.

When NSLS II commissioning is complete, it is expected that X-ray beam brightness will be $\geq 10^{21}$ [photons/sec -0.1% bw-mm²-mrad²] Photons. After commissioning it is anticipated that brightness may be increased as technology evolves over the useable life of the new light source, so that it may continue to offer it’s users the brightest beams for as long as possible. It would be unfortunate for any facility to have its brightness and flux limited by the thermal restrictions of its insertion devices. It would be desirable for the SCU to be a robust device with ample thermal operating margin, so the insertion devices will not impede upgradeability in the years to come. A thermal safety factor of at least an order of magnitude is highly desirable to accommodate the uncertainties of the heat load estimates and to assure reliability over the course of machine operation.

BNL is currently involved in intra-laboratory collaboration to develop SCU technology addressing the ultra high cryogenic heat loads that will be present in future high brightness synchrotron radiation sources. Three avenues of SCU research are being investigated by the intra-laboratory collaboration.

Lawrence Berkeley Laboratory has produced and tested the first prototype undulator magnets utilizing Nb₃Sn superconducting cable [3] Nb₃Sn has a higher critical current density than conventional NbTi superconductors and it will maintain adequate current carrying capacity at temperatures of 8K see Figure 1. At this temperature, commercially available cryo-coolers can extract heat loads in excess of 5 watts from a cold mass.

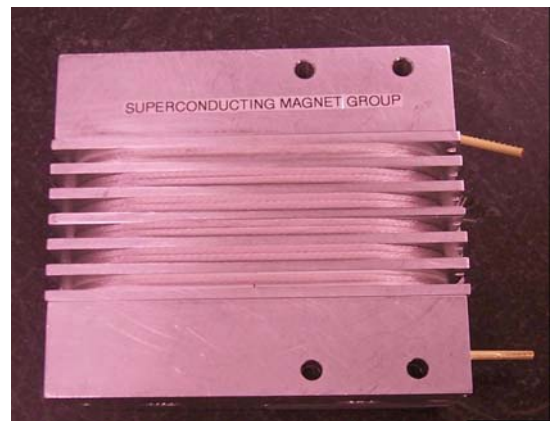


Fig 1 – 3 period, Undulator Prototype fabricated by LBL

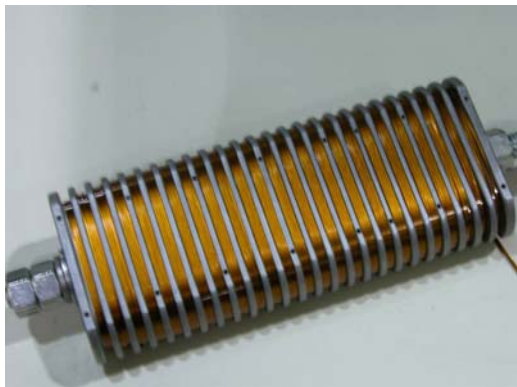


Figure 2 – The ANL 12 Period Undulator Prototype

Argonne National Laboratory has produced a segment of undulator yoke using conventional NbTi superconductor [4]. Liquid helium cooling tubes are used to cool the iron yoke of the magnet. It is proposed to use a helium refrigerator to circulate liquid helium through the yoke. Refrigerators can be obtained with adequate cooling capacity to maintain the cold mass temperature at approximately 4K see Figure 2.

BNL has proposed to construct an undulator utilizing advanced pinning center NbTi superconductor. This type of superconductor has a current density similar to that of NbSn. Methods of field correction and shimming will also be investigated and developed by the participating laboratories. See Figure 2.

3. Vertical Test Facility

A test facility is being fabricated to evaluate the prototype undulators produced by collaboration. members. The test facility is designed to simulate the environment and heat loads that could be present in an actual undulator.

Magnetic Measurements and System Controls

Three measurement methods of are being developed for incorporation into the test facility. The primary field measurement system will be an array of hall probes. Six precisely positioned hall probes mounted to a substrate will map the field of the undulator. See Figure 3. The center hall probe measures peak field. The outer two hall probes detect field flatness and symmetry. The second set of three probes confirms the readings of the first set. A stepper motor drive system positions the array along the axis of the undulator.

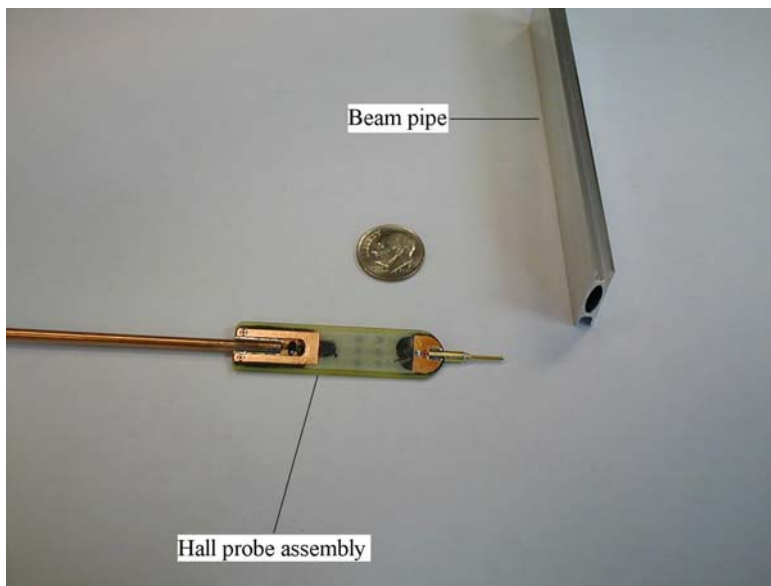


Figure 3 Hall Probe Array Assembly

A vertical pulsed wire system is being developed to perform integral field mapping and particle trajectory measurements. The pulse wire system may be altered to allow vibrating wire operation. Complementary field measurement methods will be used to fully categorize the magnetic field in the aperture of the SCU.

The unique nature of the Vertical Test Facility is evident in the type and variety of tests conditions required to simulate SCU operation. LBL and ANL prototype magnets are first tested by the respective institutions in the conventional manner utilizing pool boiling liquid helium. The magnet's performance will be evaluated and a baseline performance will be established.

The mechanical, magnetic and operational constraints on an actual insertion device indicate that liquid helium free operation is highly desirable; therefore, a cryogen free magnet performance measurement is designed into the (VTF).

Upon receiving the SCU at BNL A special point field magnet will be surveyed and fixed to the magnet yoke. The point field magnet will produce a field maximum on the magnet's geometric center axis; its position will be verified by warm pulsed wire bench tests prior to the installation into the VTF. A second point magnet is fixed to the Heimholz coil assembly which is aligned at room temperature and fixed to the bottom face of the SCU. The magnet will then be installed in the VTF. A liquid nitrogen pre-cooling, followed by a helium gas pump and purge sequence will bring the magnet and VTF components to cryogenic temperatures. Liquid helium will be transferred into the test dewar until all cold surfaces are submerged. The magnet can be tested with a current of up to 1000 amperes to re-establish the base line operating performance. The hall probe assembly will first be *insitu* calibrated using a superconducting Heimholz coil located below the SCU magnet.

The hall probe array is injected into the cold beam tube. A diagram showing this operation is shown in Figure 4. The array reading is taken and then the array is moved to the second point magnet. The hall probe array (HPA) slides without clearance on the inside of an extruded aluminum tube. A horizontal probe position will be adjusted using a linear stage located at the top of the VTF. An electric contact at the end of the probe indicates the extreme position of the HPA. The stepping motor drive system will then pull the probe up through the 4.2K beam tube past the Heimholz calibration coil and the first point magnet. The hall voltage will be monitored and a

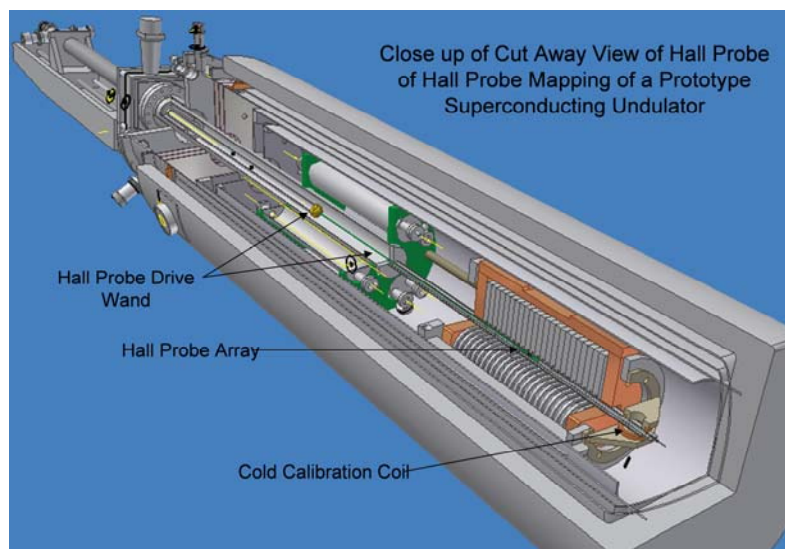


Figure 4

maximum on the probe will indicate the hall probe chip is at its nearest approach to the point magnet. The axial position of the point magnet is fixed with respect to the first pole of the SCU. The axial position of the hall probe is accurately known relative to the magnet iron geometry. The HPA will be drawn through the magnet until it reaches the second point magnet. The axial positions of the two are controlled by Zerodur rods which are in turn fixed to the outside of the magnet. Knowing the exact distance between the point magnets and their relative position with respect to the SCU prototype assures that we will have hall probe positioning which is essentially independent of temperature gradients and the corresponding length uncertainties in the HPA drive shaft.

Upon completion of initial field mapping and baseline performance testing, the VTF will be pressurized with helium gas and the liquid helium that does not boil away will be transferred back into the storage dewar. A heater at the base of the VTF will assure that all liquid is boiled away. The fill/extension transfer line will be valved off and the transfer is withdrawn from the dewar.

The next operation is highly dependent on the design of the magnet and the specific cooling concept. In the case of LBL SCU prototype, a copper cooling plate may be affixed to the magnet iron so that heat may be removed from the magnet by conduction between the chill plate and the magnet iron liquid helium or cold helium gas at $\approx 8\text{K}$ can be circulated through the chill plate. The ANL SCU prototype cooling tube in the yoke will extract heat by convection from the inside of the yoke. A helium cooling line attached to the cold

mass will allow liquid helium with a temperature range of 3.2 to 5.2K to be supplied to the cold mass. A precision heater is affixed to the surface of the HPA tube. When the heater is turned on the heat generated will simulate the heat deposited into the actual beam tube from eddy currents, gas beam scattering and stray synchrotron radiation. The heater is designed to deliver up to 100 watts/meter to the gap of the SCU prototype.

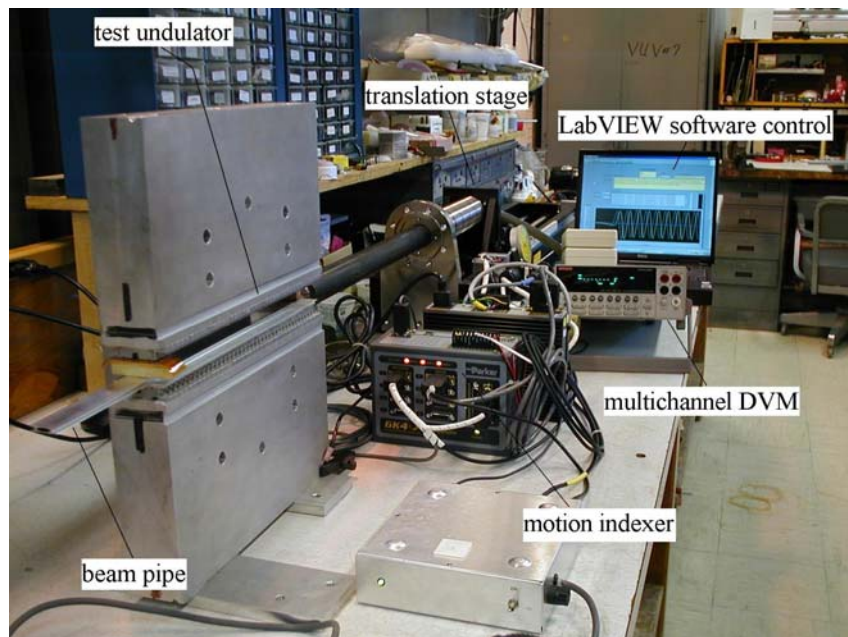
There are up to 3 cooling loops that can supply liquid or cold helium gas to the magnets cold mass to evaluate magnet cooling concepts. Calorimeters are located in the flow path just down stream of the cold mass. The calorimeters are extremely important to determine the heat that is deposited in the cold mass and the effectiveness of the magnet's cooling concept.

Hall Probe Mapping Assembly

The Hall Probe Mapping Assembly consists of a 6 element printed circuit Hall array secured to a copper support tube, which is affixed to a Z-axis stage. The individual Hall elements are tiny surface mount devices, which have an active area approximately 125 microns by 125 microns. They are arranged in two rows of three elements, thus on-axis and off-axis data can be taken in a single scan. The twisted-pair wires which deliver the excitation current to the sensors and transport the detected Hall signals run along the inside of the copper support tube to provide shielding from electromagnetic interference.



The Hall signals from the 6 sensors are sampled by a high precision, programmable, externally triggered, multi-channel voltmeter with a large buffer. The Z-axis stage is driven by a motor, which is software controlled.

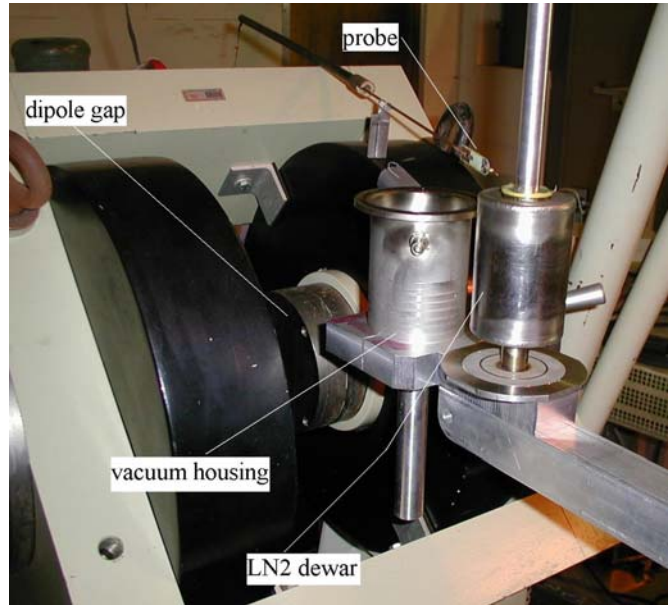


The Hall probe scan is done “on-the-fly”: the Z-axis stage is homed precisely, the motor is instructed to move at constant velocity and the voltmeter is periodically triggered by the divided motor step signal to scan sequentially to buffer all 6 channels. The “on-the-fly” scanning speed is constrained by the spatial field resolution required--the number of samples per undulator period--and the integration time of the measurement to achieve the desired accuracy, which is constrained by the interference

in the Hall signals. Typically a full scan--1/2 meter--can be done in about 4 minutes. The Hall voltage data is converted into magnetic field information by post-processing with respect to the polynomial fitting of the NMR calibration data for each sensor.

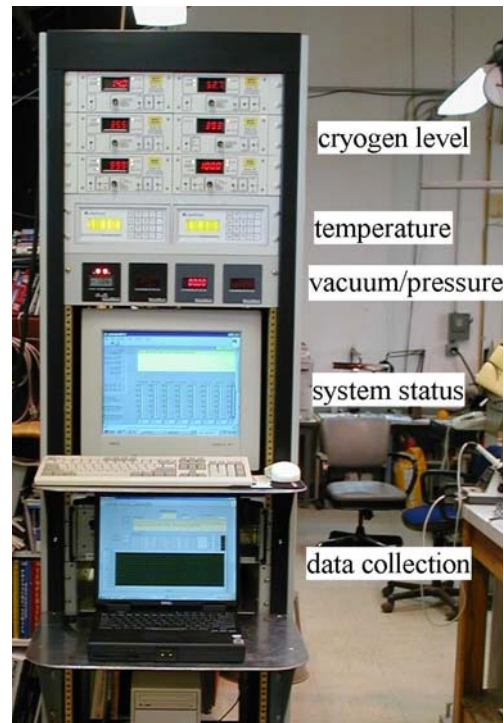
Hall Probe NMR Cold Calibration

All six of the Hall sensors on the Hall probe assembly were calibrated in the NMR at room temperature and then at 77 * Kelvin over a field range of + and – 1.1 Tesla. The cold calibration was done by submerging the probe in liquid nitrogen, which was contained in a small dewar, which was inserted into the NMR field. The dewar was designed to fit along with the NMR probe in the 1 ½ inches (38mm) gap between the NMR calibration magnet poles.



Vertical Test Assembly Instrumentation

The Vertical Test Assembly Instrumentation rack configuration was designed to be robust and portable. Using National Instruments LabVIEW software, all of the critical system parameters are monitored and controlled, like temperature, vacuum and pressure, cryogen level and flow, superconducting current path resistance, and embedded heating elements. All of the monitored parameters are displayed close to real-time, so that the state of the system is well defined at any given time, and so that calorimetry and heat loading calculations can be performed. Also, the information is continuously logged to spreadsheet for post-processing and analysis.



Calorimeter Operation

The purpose of the calorimeter is to determine how much heat has entered a particular liquid helium flow stream. This is necessary to determine the effectiveness of SCU cooling methods. There are three calorimeter

cans in the VTF, one per each possible helium flow path. Each calorimeter is composed of a cylindrical tank with a volume of approximately 1 Lt. with an accurate inside diameter. A helium liquid level probe runs the length of the can. A calibrated Cernox temperature sensor is positioned in the helium flow stream just below the can. A 100 watt heater is located in a separate line near the bottom of the can, but is isolated from the Cernox probe. A second Cernox probe is located in the flow path just prior to entering the cold mass.

The principle of operation can be formulated as:

$$Q = M c_p \Delta T$$

Q = Heat

M = Mass flow rate

c_p = Specific heat

ΔT = Change in temperature

A precision pressure transducer measures the pressure of the gas flow down stream of the calorimeter can. Specific heat " c_p " can be deduced by knowing the temperature and pressure of the helium flow. The liquid level sensor monitors the change in liquid level inside the calorimeter can. ΔT is the change in the helium flow temperature across the cold mass. Q in watts may be obtained by monitoring the above parameters and applying the formula. One drawback to the design is that it is a batch process. Once the helium can is full the heater is turned on to boil the liquid until the level in the can is nearly empty, but it is an accurate alternative to highly expensive liquid helium flow meters that will have significant error for this application. The pressure control valve has been designed to accommodate the increase of helium flow during boil off, and a check valve in the line between the cold mass and the calorimeter prevents the back flow of warm gas back through the cold mass.

Sub-cooler Operation

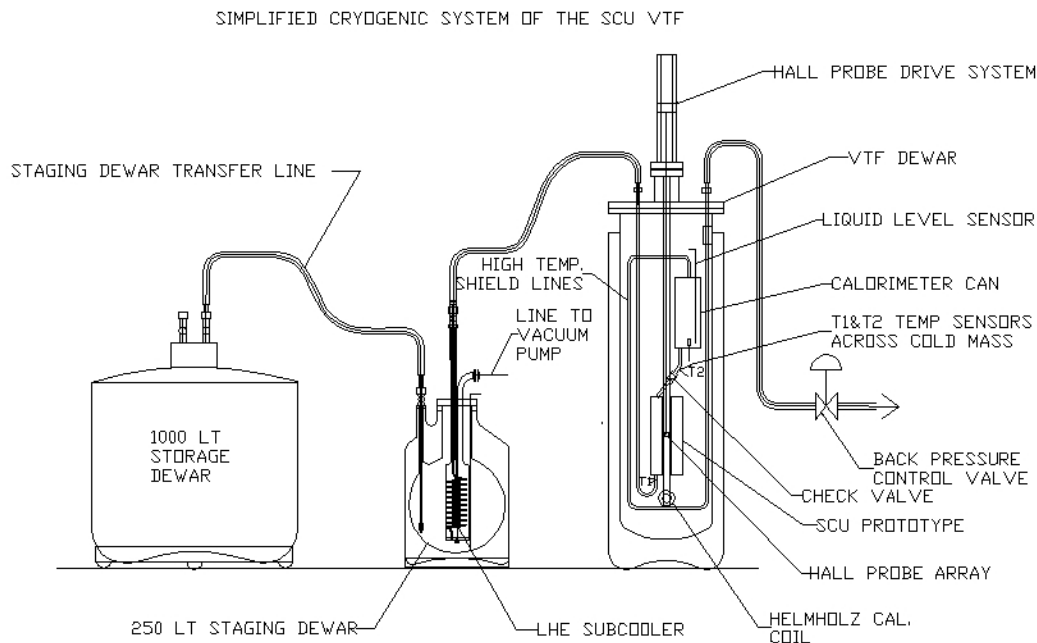
To perform effective calorimetric measurements helium liquid must be sub-cooled to allow a template rise without phase change. To control the temperature of liquid helium, a sub-cooler insert will be installed in the high pressure staging dewar. The staging dewar is designed to have an operating pressure up to 50 psig. By pressurizing the staging dewar, the temperature of the liquid could be increased to the critical point of $\approx 5.3\text{K}$. The sub-cooler is a small vessel with valves in the 250 Lt. helium staging dewar. When the valve is opened, liquid enters the sub-cooler vessel. A liquid level sensor monitors the level until the level covers and heat exchanger coil. The valve is then closed and a partial vacuum is applied to the sub-cooler vessel. The vacuum allows the helium to boil, and the temperature can be dropped to as low as 2.5K. Helium in the high pressure vessel is then allowed to flow through the heat exchanger coil in the sub-cooler. A calibrated Cernox sensor at the exit of the heat exchanger coil monitors the liquid temperature. The overall flow is controlled by the pressure control valve and a valve at the base of the liquid helium transfer line between the sub-cooler and the VTF test dewar.

3. Detailed description of VTF operation

The cryo system of the VTF has three open loop helium flow paths. At its maximum the system is composed of the following:

- two each 1000 LT portable dewars,
- three 250 Lt. pressurizable staging dewars.
- A sub cooling heat exchanger is located in each 250 LT dewar
- Liquid helium transfer lines for each staging dewar
- Liquid helium lines for each supply dewar
- transfer line stubs
- re-sealable feed throughs located on the top hat plate of the VTF

A simplified diagram of a single helium flow path and system components is shown below in Figure 5.



Stainless steel plumbing lines direct liquid cryogenics to the following locations within the VTF:

1. The base of the helium dewar.
2. The independent helium reservoir of the pair of 1000 amp vapor cooled leads.
3. The HPA tube vacuum chamber.
4. The helium cooled magnet cold mass chill plate or vessel.
5. Magnet cold mass cooling lines.

The helium lines pass through the beam tube and cold mass plumbing into calorimeter cans. The flow path exits the calorimeter cans and enters lines that run through a low temperature aluminum shield. Up to two flow paths can run through the shield so that helium exhaust gas is always cooling the shield.

After leaving the shield the gas flow path enters a thermal heat stationing ring. This copper ring rests against the wall of the vertical test dewar. Its' purpose is to intercept heat entering through the top of the dewar and traveling down the dewar's inner wall. The heat stationing ring in effect establishes a high temperature heat shield, so that a liquid nitrogen bath on the out side of the dewar's vacuum envelope is no longer needed. This greatly simplifies cryogen handling, safety and space issues around the test dewar.

Upon leaving the heat stationing ring the flow path exits through a re-entrant feed through out of the vacuum/helium space of the dewar, through its top hat. A flexible metal hose directs the flow to the CPC cryo lab pressure control valve. This back pressure control valve controls the pressure through the VTF's cryogenic system. Upon exiting the control valve the helium flow enters the building 902 Magcool refrigerators helium recovery system. After cleaning, compression, and liquefaction the helium liquid fills the 1000 lt. storage dewars.

4 VTF Testing Procedures

The magnet and beam tube assembly is brought to liquid helium temperature and base line performance is re-established. Liquid helium flow rate through the sub-coolers, cold mass and calorimeters is established and stabilized base line conditions. The magnet is brought to the desire field level and magnetic measurement

utilizing the hall probe array and/or pulsed wire system is performed. After the magnet field is fully measured, thermal studies are started. The beam tube heater is turned on. The calorimeter on the beam tube cooling line is monitored to determine the total heat load deposited in the beam tube. Temperature sensors on the magnet iron and the cold mass calorimeter are monitored to detect heat being transferred into the cold mass and determine the cooling capacity of the respective cold mass cooling system. Magnet voltages are monitored to detect quench onset. This operation is performed until a stable heat transfer condition is established in the beam tube magnet cold mass assembly. If this state is re-established, this would mean, the magnet cooling system is supplying an adequate heat removal capability. Upon completion of this step additional current is applied to the heater in the beam tube. All systems are monitored to determine if the heat loads in the beam tube and cold mass are understood and if the magnet is nearing a quench threshold at this additional heat load. This step is repeated until quench or a near quench threshold event occurs. When a quench is determined the current on the magnet is dumped to a resistor by the magnet's quench protection system. The test may be repeated with different temperature and or flow rates of liquid helium through the cold mass to determine the total thermal operating envelope of the prototype magnets cryogenic cooling system. Magnetic measurements may be performed to determine if any field changes occur at these extreme conditions.

Once the prototype has completed these tests it will be removed from the VTF and returned to the contributing institution and the next prototype will be made ready for magnetic and thermal measurements. This operation will be repeated for all the undulators BNL and/or the collaboration members' supply for testing. Higher temperature operation can be achieved for testing Nb₃Sn coil undulators by running cold helium gas to the magnet cold mass a beam tube. The sub-cooler will be fitted with a heater to vaporize the liquid helium flow. Cold gas will then be transferred through the magnet cold mass. The calorimeters' temperature sensors will be used to determine the change in temperature of the gas stream across the cold mass. A calibrated helium mass flow meter will be installed into the flow path down stream of the VTF. The precision flow meter operates at near room temperature so the gas stream must first pass through a gas or air heat exchanger prior entering the flow meter. At the completion of the SCU prototype program, several different SCU magnet and cooling concepts will be characterized experimentally. Confirming the thermal operational envelope will allow engineers to make appropriate selection of specific cryogenic systems to maintain the operating parameters of selected magnets.

When the initial cryogenic magnetic measurements program is completed, the VTF is planned to be modified to incorporate a cryo-cooler and closed loop helium circuit flow components to allow the testing of proposed cryogenic systems as well as the magnet. A cryo-cooler or liquid helium heat exchanger would occupy the same location that the magnetic measurements systems currently occupy. The VTF can then test components of integrated system to demonstrate their performance prior to or in parallel with full scale insertion device development.

5. Conclusion

A Vertical Test Facility capable of simulating the heat load of current and future high brightness synchrotron radiation sources is being assembled by the NSLS Department at the Brookhaven National Laboratory. The facility will be able to fully measure and categorize the field of a superconducting undulator magnet up to 0.5 meters in length using several field measuring methods, which includes a hall probe array, a pulsed wire and possibly a vibrating wire system. The system will be able to measure the heat load deposited in the magnets' cold mass from a heater in the magnet gap, which simulates image currents, synchrotron radiation, and other phenomena up to 100 watts per meter can be simulated by this system so that the thermal operating envelope of perspective SCU designs may be experimentally conferred and /or evaluated so that appropriate cryogenic refrigeration systems may be selected.

Acknowledgements

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Special to thanks goes to Lydia Rogers in the preparation of this paper.

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DISCRIPTION OF EXPERIMENT

BACKGROUND AND INTRODUCTION

The operation of the proposed NSLS II as a world class, state of the art, third generation synchrotron radiation source is highly dependent on the use of insertion devices that are located in the ring between each super-period. The performance of many of these insertion devices will be dependent on the operation of superconducting undulator (SCU) magnets.

SCU's in the proposed NSLS II will be subject to potentially high heat loads as compared to conventional superconducting devices. Heat loads on the order of tens of watts per meter have been estimated but a precise analytical prediction as of yet can not be produced.

SCU's have been built here at BNL, other laboratories and industry but none of these designs have addressed the high heat loads that will be unique to NSLS II.

The SCU Vertical Test Facility (VTF) was designed as BNL's contribution to a national collaboration formed with three other national laboratories. Magnet prototypes were to be fabricated by two of these laboratories and delivered to BNL for magnetic and performance measurements.

Due to lack of funding developmental efforts at the collaborating labs has slowed and prototypes specifically for testing by the SCU VTF have not been delivered to BNL and none are anticipated in the near future. Unlike the other laboratories that have a scientific interest but no specific application the development of heat load compliant SCU's are highly desirable for use in NSLS II.

Recently an LDRD has been approved to develop a BNL SCU design specific for use in the proposed NSLS II. This a two year LDRD program and a completed prototype is not anticipated until the second year.

The VTF is designed to perform magnetic measurements with two different field measurement techniques.

A hall probe array and a pulsed wire system has been constructed and will be tested by evaluating the field of an early SCU that was designed and fabricated at BNL approximately 10 years ago.

This undulator will product a magnetic field similar to the actual SCU and will be adequate to perform measurement systems acceptance testing but has no other means of cooling other then pool boiling.

There fore only the magnetic measurement systems can be tested and the thermal measurement aspects of the VTF can not be tested at this time.

The testing of the VTF will occur in two phases and NSLS seeks approval for the first phase of magnetic field measurement tests which involves LHe pool boiling tests at atmospheric pressure.

The following paragraphs present a draft test procedure for review.

SYSTEM DISCRIPTION FOR PHASE ONE TESTING

The initial phase one testing will involve pool boiling tests of a short section of undulator magnet about 17 cm long. The undulator will be fixed to the end of the VTF top hat assembly. The actual cold mass shall comprise the undulator, a calibration helmholtz coil assembly. An iron knife edge magnet and an aluminum featuring plate that locates all these components together relative to the top hat and the magnets bore tube.

The current plan is to have all these components wired in series and operated at approx. 160 amperes.

The top hat assembly will be inserted into the 63 inch deep Sampson dewar. Two 250 liter dewars manufactured by Cryofab will used to supply and maintain the LHe level in Sampson's dewar. The supply dewars have been designed to the ASME pressure vessel code but are not stamped. The maximum operating pressure of the storage dewar is 35 psig.

Less then 65 liters of pool boiling liquid Helium will submerge the magnet assembly.

A valved transfer line made by the Janus Co. will be used to transfer LHe between the 250 liter Cryofab storage dewar and the test Dewar. The stab extension line will run to the bottom of the dewar where filling will occur. The stab extension line has a valve that once opened can divert flow into a pair of 1000 ampere vapor cooled current leads made by the American Magnetics Company. An oilless vacuum pump will be used to supply a vacuum to the exhaust ports of the gas cooled leads. The leads will pumped a purged with helium gas to prevent internal icing. A liquid nitrogen transfer line and level sensor manufactured by American Magnetics will be used for precooling. Less then 120 liters of liquid nitrogen will submerge the magnet, vapor cooled lead vessels and other structural components of the VTF. Pressure and vacuum sensors shall monitor pressure in the supply and test dewar.

CRYOGENIC OPERATION

The 250 Lt. storage dewar will be filled at the at the liquid Helium refrigerator located at 902. The storage dewar will roll manually approximately 100 feet to the testing area which shares the same building volume as the 902 refrigerator.

Liquid nitrogen will be used to precool to cold mass of VTF and the inside wall of the test dewar. LN2 may also be used in the outer shield of the test dewar.

Liquid nitrogen will be supplied to the test dewar until the LN2 liquid level probe indicates the level in the dewar is stable and has submerged all LHe bearing components. All ports into the dewar except the exhaust port and relief lines will be purged to prevent contamination.

Helium gas at approximately 5 psig will then be supplied to the top hat to force the transfer of LN2 back into the LN2 storage dewar. When the LN2 level indicates zero level, A heater at the bottom of the dewar will be activated to assure complete boil off of the LN2.

The LN2 supply valve shall be closed and the system shall be pumped and purged with helium gas 3 to 4 times to assure there is no N2 left in the system.

Under a positive helium gas pressure the valved end of the Janis transfer line will be used to stab the storage dewar.

While under positive He gas pressure in the test dewar the output end of the transfer line is inserted into the test dewar and o-ring seals are made on either end of the vacuum jacketed transfer line.

The valve to the 902 Helium gas recovery system is opened and the positive pressure helium gas escapes into the recovery system.

The valve on the transfer line in the supply dewar is opened to allow gas and then liquid to be transferred into the test dewar filling the test dewar to a level covering the magnet up to the bottom of the vapor cooled current leads.

When the liquid level is stable the valve in the supply dewar will be choked to provide a trickle flow into the test dewar. A vacuum pump shall be used to evacuate helium gas from the storage vessels of the vapor cooled current leads.

The valve in the test dewar stab extension shall be opened to allow LHe from the test dewar to fill the lead vessels. Liquid level sensors in the lead vessels will indicate LHe level and manual control valves on each of the process vacuum lines can be used to adjust individual vessel LHe levels. A maximum of 1 Lt. of LHe will be maintained in each of the lead vessels during the test.

Voltage and current taps on each of the components in the Superconducting circuit shall indicate when all components are Superconducting. When this state is reached and confirmed magnet testing shall commence. At a ramp rate of 1 amp per second, a current level of 160 amps is established in the circuit.

The hall probe array shall be inserted into the evacuated beam tube where it will be first be calibrated then moved to a knife edge magnet to establish exact axial position, the array will then be moved through the undulator for field mapping to take place. The hall probe array is then moved to a second knife edge magnet to establish precise cold travel distance. The probe will then be moved into a zero gauss chamber. The magnet current shall be ramped to zero current and the process repeated until Hall probe array testing is completed.

The storage dewars have two fill ports and built in liquid level sensors so that LHe liquid can be supplied to the primary storage from a second supply dewar without having to disconnect the transfer line to the test dewar.

When the Hall probe mapping is completed the current to the vapor cooled current leads is ramped to zero.

The stab line extension valve is closed and the valve to the 902 helium recovery system is metered to allow a pressure build-up not to exceed 5 psig in the test dewar while the valve in the storage dewar transfer line is opened. This action transfers the approx. 60 liters of LHe back into the storage tank. Liquid level and pressure in the storage tank is monitored and controlled to prevent any overflow condition.

When the test dewar liquid level is zero a heater in the bore tube and the bottom of the test dewar will be activated to assure all LHe has exited the tank. The pressure in the test dewar and the valve position in the storage dewar to could be adjusted to maintain a cold transfer line. The evacuated bore tube will be filled with helium gas. While under Helium gas purge the Hall probe array assembly will be removed from the top hat assembly.

The pulsed wire probe will be inserted into the purged bore tube and the probe mechanism shall be secured and sealed to the top of the top hat. The interstitial space between the bore tube and the pulsed wire probe tube shall be evacuated and the bore tube heater shall be turned off. The time of this change over shall be kept to a minimum to assure that the majority cold mass temperature does not rise above LN2 temperature.

The valve to the 902 helium recovery system is opened while the transfer line valve is opened in the storage dewar.

LHe is allowed to enter the test dewar cooling the cold mass components until the magnet assembly is again submerged and the LHe level reaches the bottom of the gas cooled leads. The storage dewar valve is metered to a trickle and the vapor cooled lead valve is opened. The process vacuum in the vapor cooled lead vessels draws in LHe from the test dewar until a maximum of 1 lt. of LHe will be maintained in each of the lead vessels. Voltage and current taps on each of the components in the Superconducting circuit shall indicate when all components are Superconducting. When this state is reached and confirmed magnet testing shall commence again. At a ramp rate of 1 amp per second, a current level of 160 amps is established in the circuit.

In the pulsed wire system a wire is located through the bore or the undulator. In this test no object moves on axis. An electric pulse is supplied to the wire. The wire actually deforms elastically in response to the magnetic field and the pulses move up the wire where they are detected and analyzed. This measurement method can actually depict the path of a simulated electron beam through the undulator magnet.

Pulsed wire measurements of the undulator shall be made until the undulator is fully mapped and the equipment operation can be confirmed. At this point magnetic measurements and verification tests for the VTF shall be considered complete.

The Current in the Superconducting magnet shall be ramped to zero amperes. The stab line extension valve is closed and the valve to the 902 helium recovery system is metered to allow a pressure build-up not to exceed 5 psig in the test dewar while the valve in the storage dewar transfer line is opened. This action transfers the approx. 60 liters of LHe back into the storage tank. Liquid level and pressure in the storage tank is monitored and controlled to prevent any overflow condition. The bore tube heater and the heater in the bottom of the tank is activated to assure there is left in or can accumulate in the bottom of the test dewar. A Helium purge is established to the test dewar vessel and the valve of the transfer line in the storage dewar is closed. While under He gas purge the Janis transfer line is removed from the test and storage dewar. The test dewar is allowed to rise to room temperature while under helium gas purge feeding into the 902 gas recovery system while the unused portion of LHe in the storage is manually wheeled back to the 902 refrigerator.